# Nanowire and Superlattice Mid-Infrared Emitters on Si

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- NSF for nanowire research under EPMD-1608714
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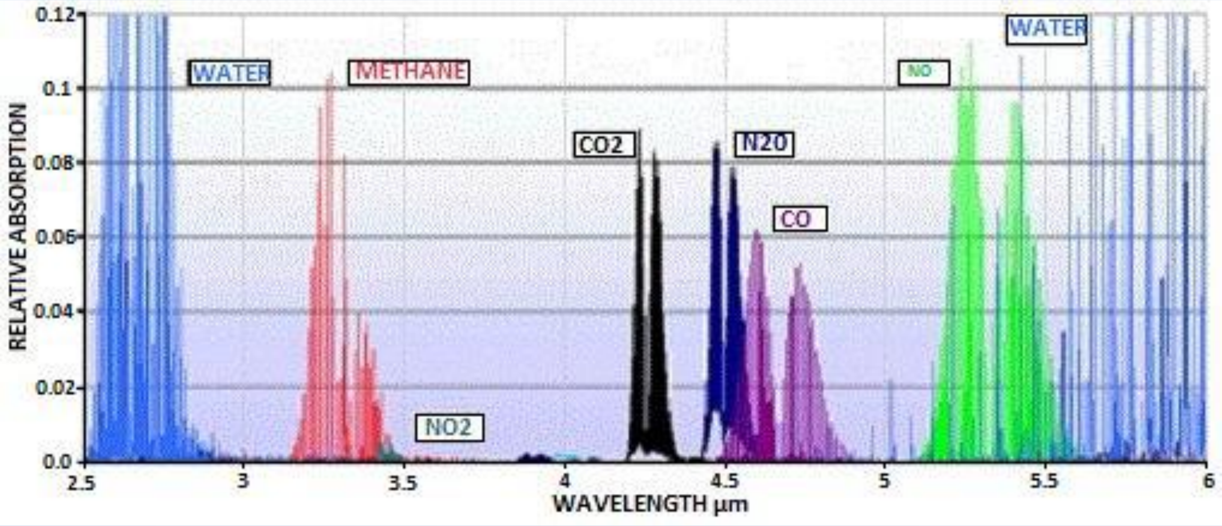
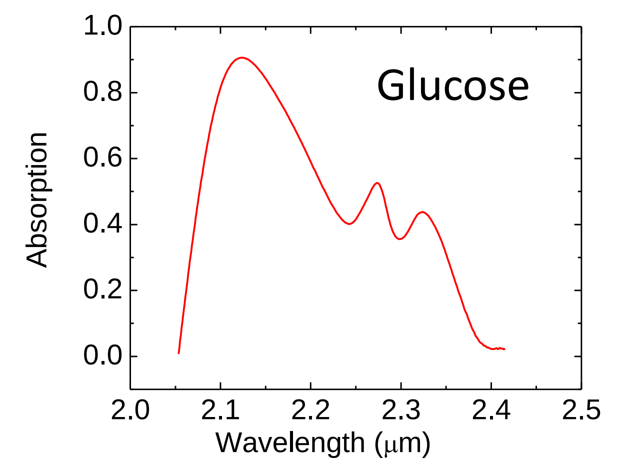
# Some motivations for mid-infrared LED development . . .

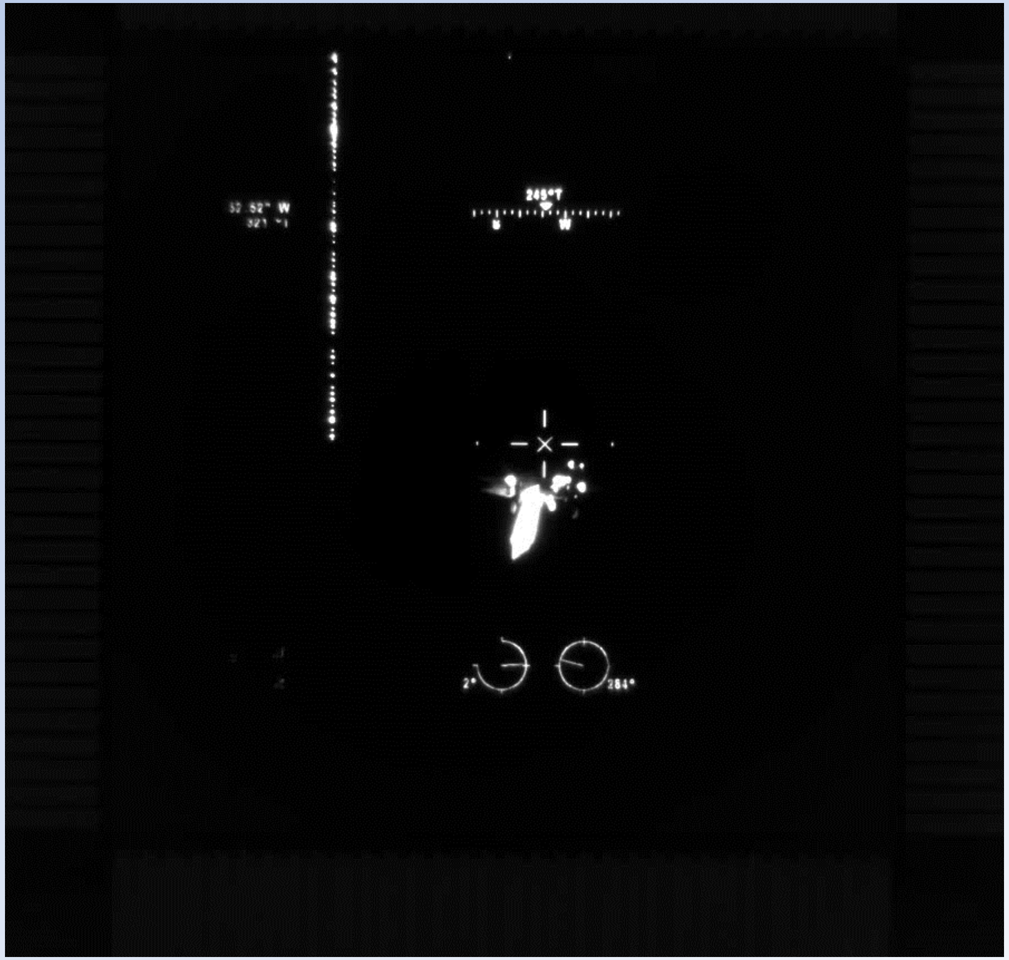
## Low cost gas sensing



Chemical sensing in aqueous



## Thermal scene generation

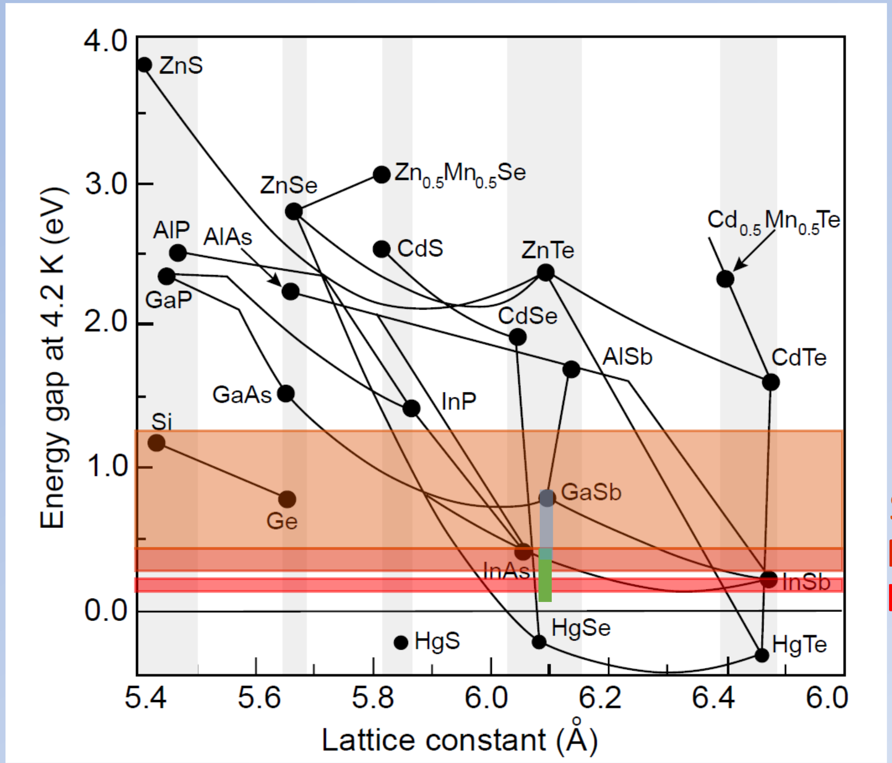


Acknowledgement of partners Chip Design Systems and Teledyne Scientific

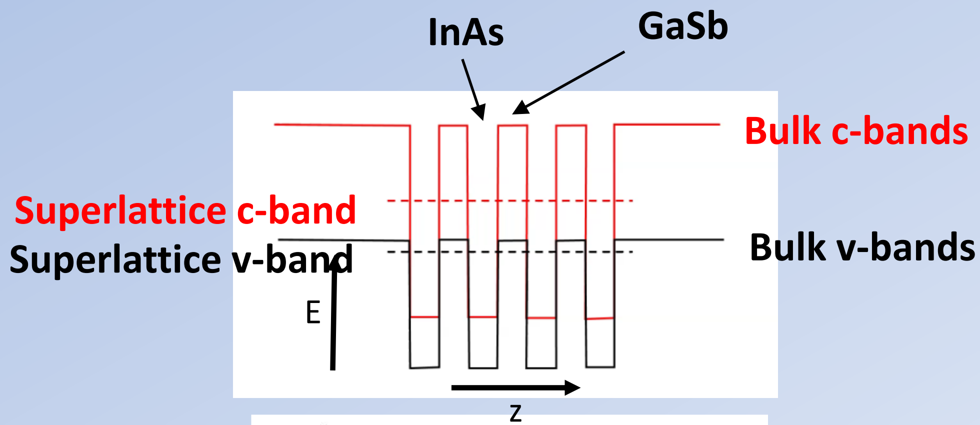
# Type II superlattices and alloy group III-Vs widely tunable over the mid and long-wave infrared

🟩 **InAs/GaSb 3-30 μm**

🟦 **GaInAsSb 1.7-4.9 μm**



SWIR: 1-3 μm
MWIR: 3-5 μm
LWIR: 8-12 μm



**InAs**

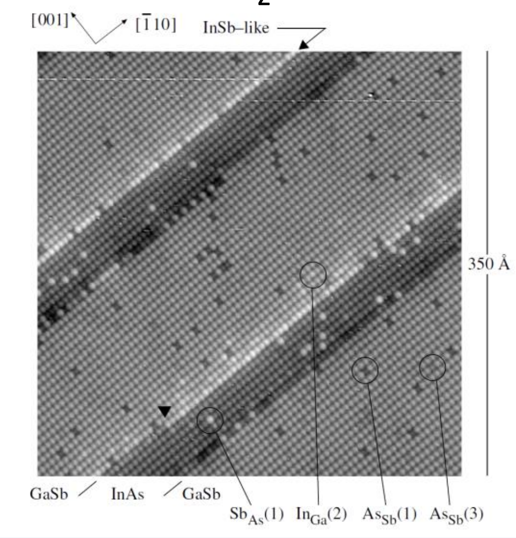
**GaSb**

**Bulk c-bands**

**Superlattice c-band**

**Superlattice v-band**

**Bulk v-bands**



STM cross section of InAs/GaSb[1]

Group III-V semiconductor materials

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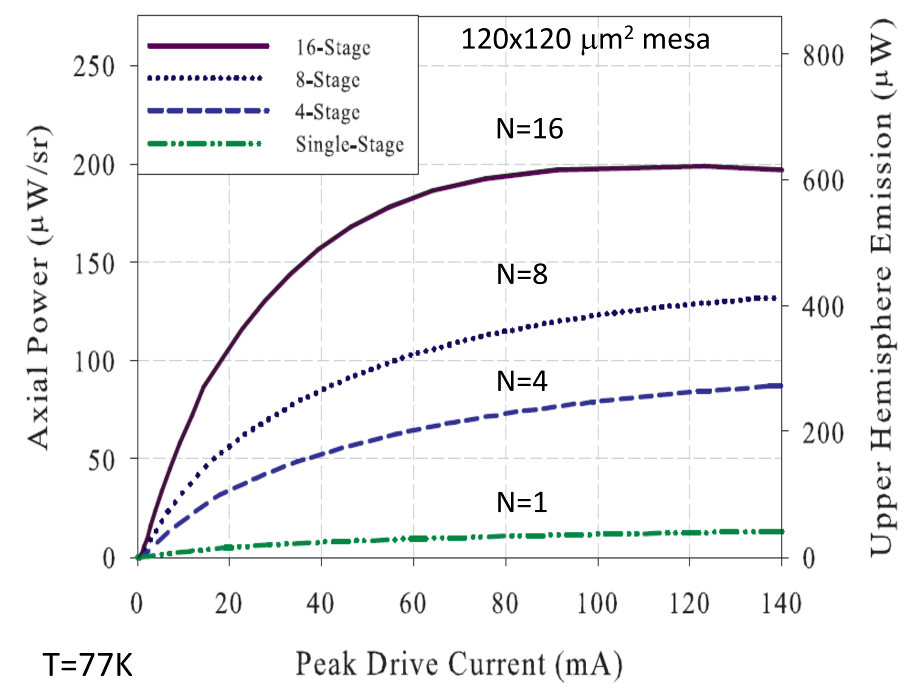
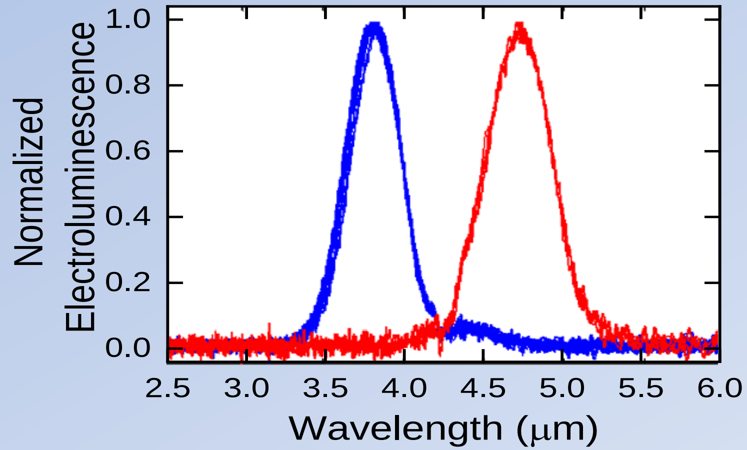
[1] Steinshnider etal, *Phys Rev Lett* **85**, 2953 (2000)

# Cascaded mid-infrared superlattice LEDs (SLEDs) have flexible emission and electrical characteristics

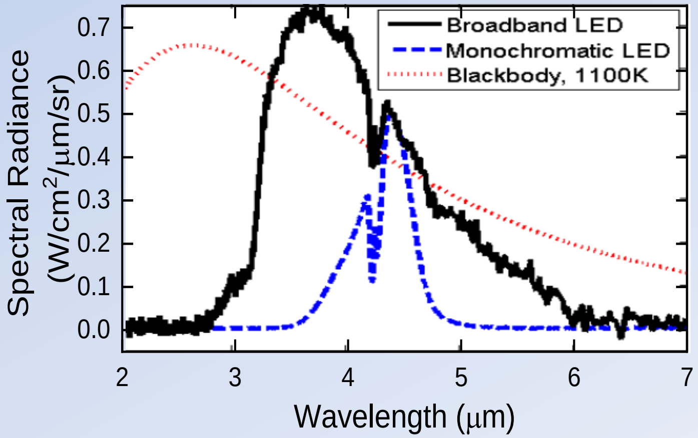
Cascading for lower current, higher voltage operation



E. Koerperick etal, J.P. Prineas, *IEEE J Quant Electron* **44**, 1242 (2008)



Independent two-color emitters



Broadband emission

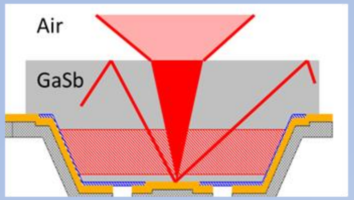
R. Ricker etal, J. P. Prineas IEEE J. Quantum Electron. **51**, 3200406 (2015)
R. Ricker etal, J.P. Prineas J. Appl. Phys. **121**, 185701 (2017)

# Growth on Si motivated in part by low efficiency and high heat generation in SLEDs

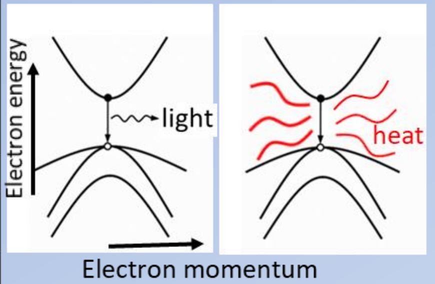
Low Efficiency

$$\eta_{wallplug} = \eta_{extraction}\ \eta_{internal\ quantum\ efficiency}\ \eta_{ohmic}\ \eta_{quantum\ defect}$$

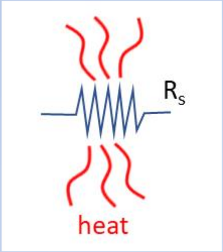
0.25% ~ 2-3% x 20% x 70% x 70%



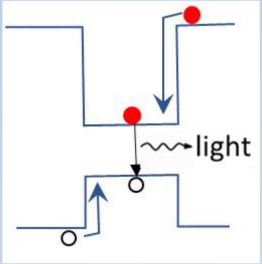
Light extraction efficiency



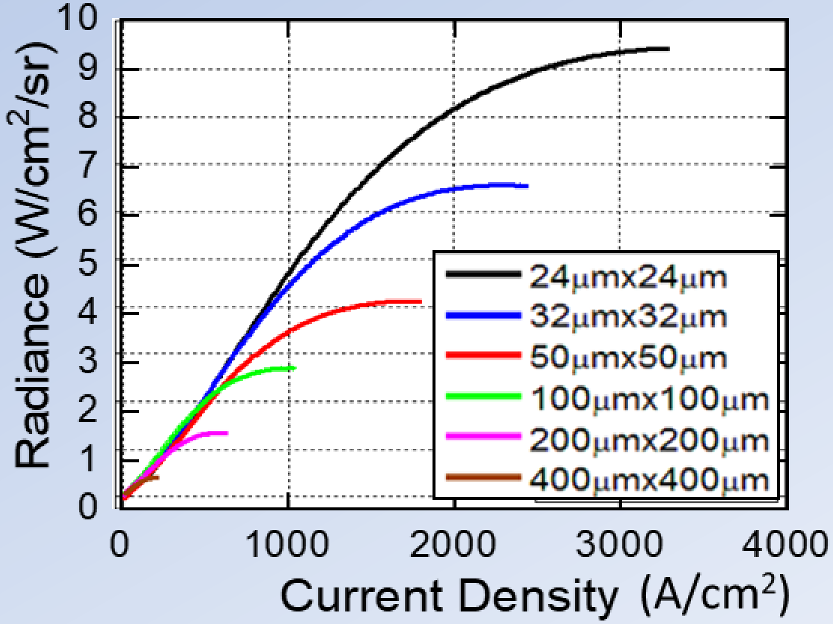
Internal quantum efficiency



Ohmic efficiency



Quantum defect efficiency

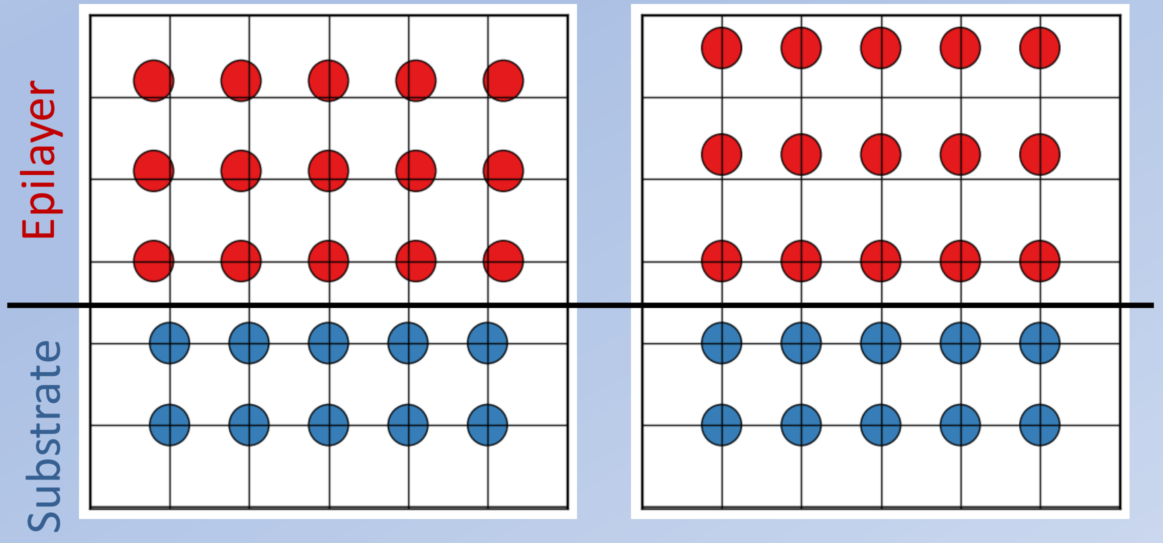

Thermal rollover

## Why Si substrates instead of GaSb?

- Better thermal conductivity (4x)
- Less absorbing (10x)
- Less brittle(2x Young's modulus)
- Potentially less expensive

# Challenges of growth of III-V’s on Si

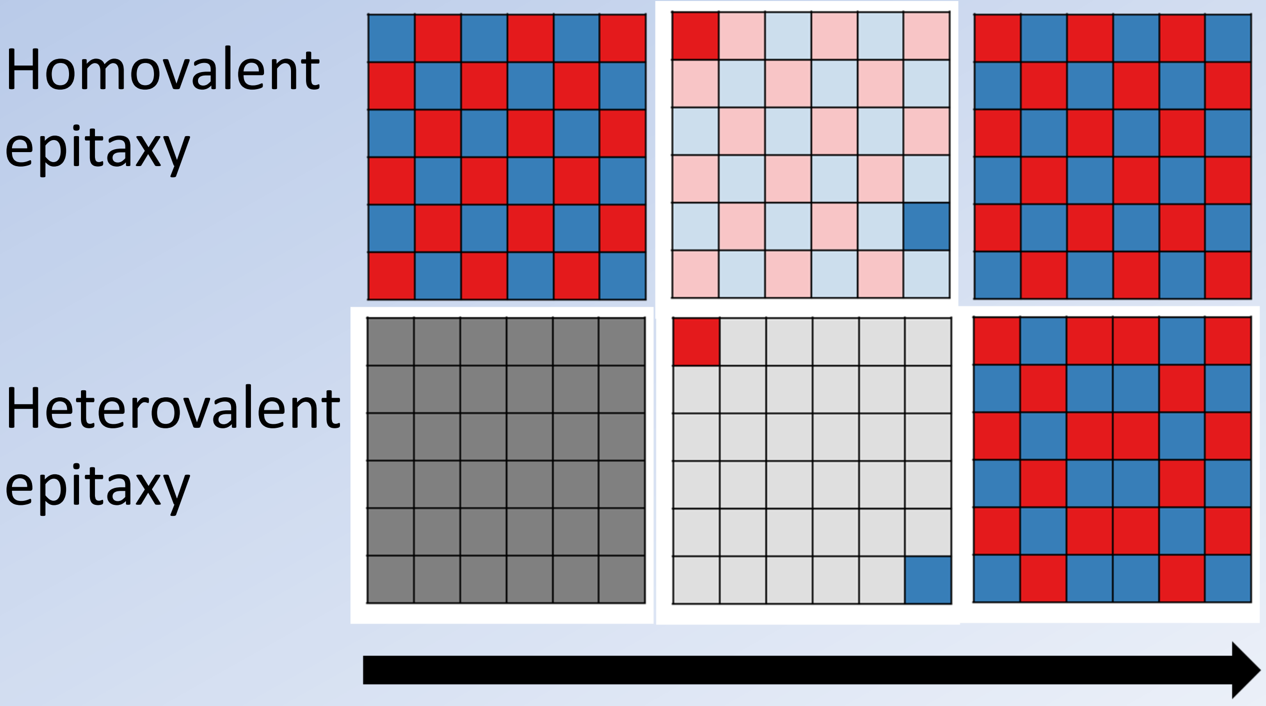
## High strain



**Mismatch to GaSb:**

- GaSb: 0%
- InAs: 0.6%
- AlSb: -0.6%
- GaAs: 7%
- Si: 11%

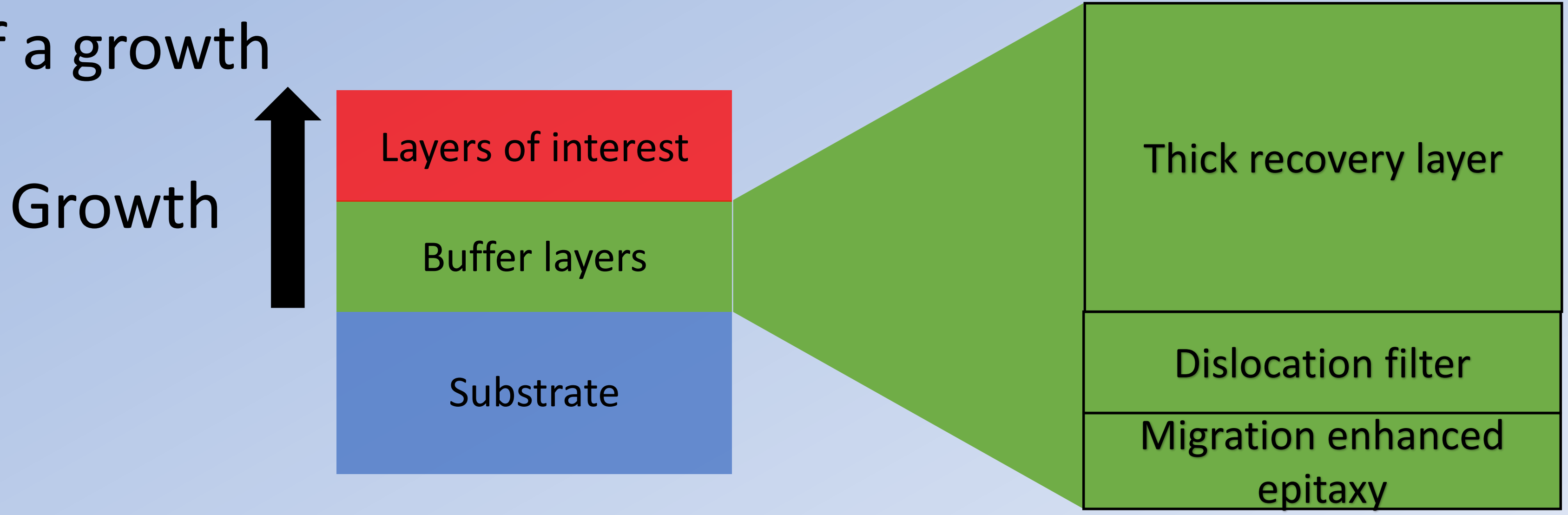
## Heterovalency



Forming a new layer

# Approach to growth of III-V semiconductors on Si

- ❖Anatomy of a growth


Growth

Layers of interest

Buffer layers

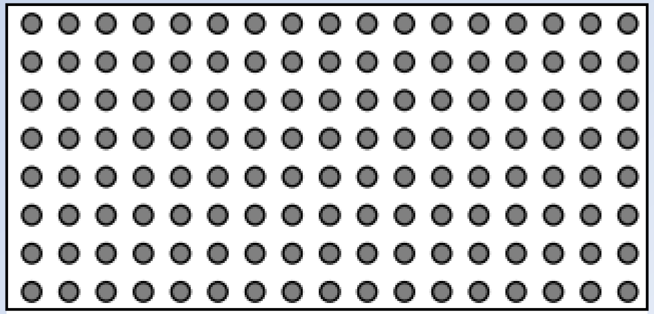
Substrate

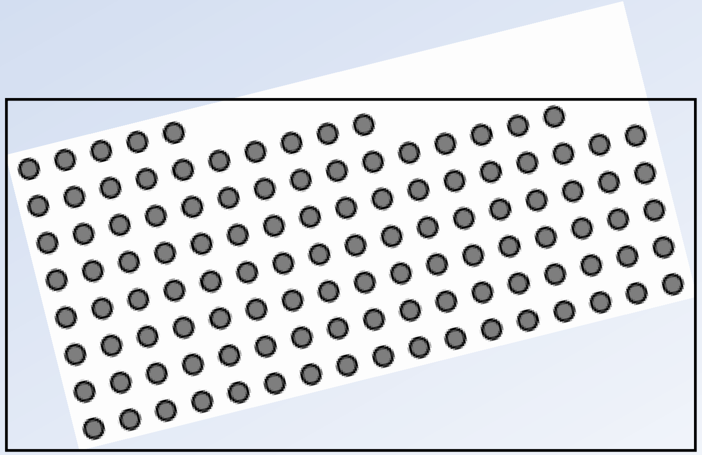
Thick recovery layer

Dislocation filter

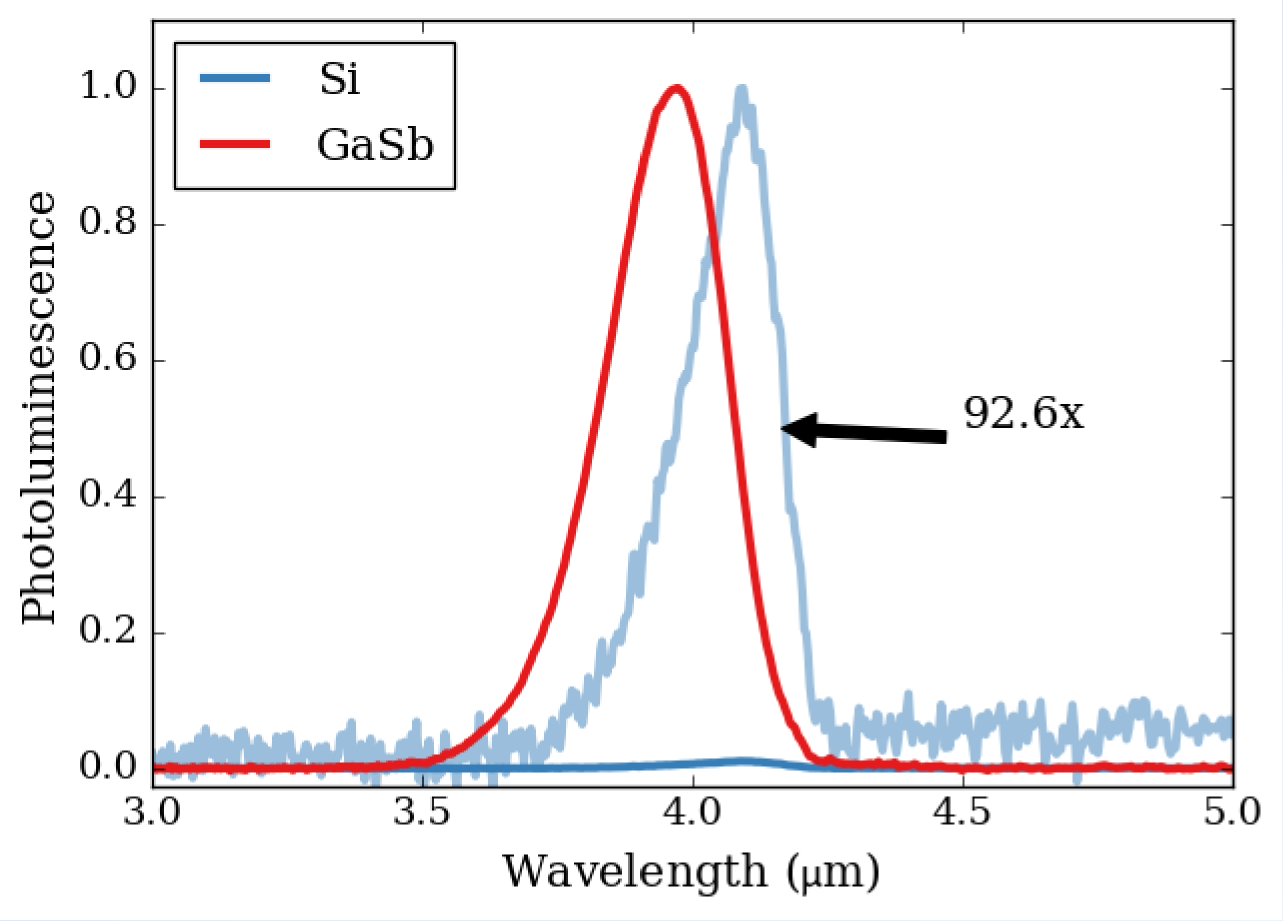
Migration enhanced epitaxy

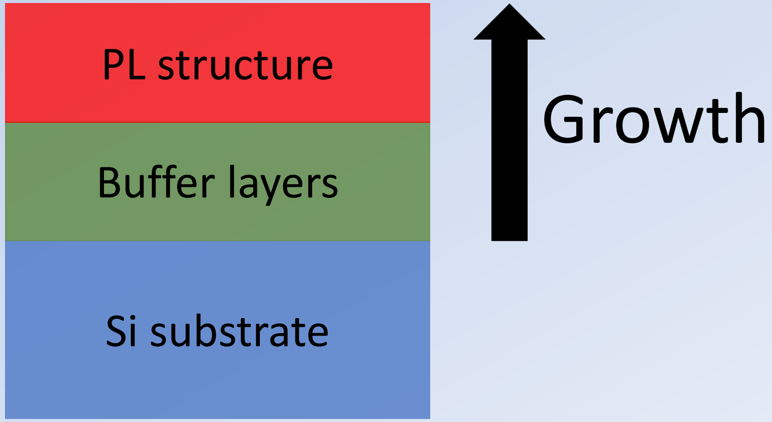
- ❖Heterovalency
  - Use miscut substrate– simulates homovalent template
- ❖Lattice Mismatch
  - Migration enhanced epitaxy
  - Dislocation filter
  - Thick recovery layer


Regular substrate


Miscut substrate

# Low material quality is evidenced by low photoluminescence from InAs/GaSb superlattice on Si vs. GaSb substrates




PL structure

Buffer layers

Si substrate

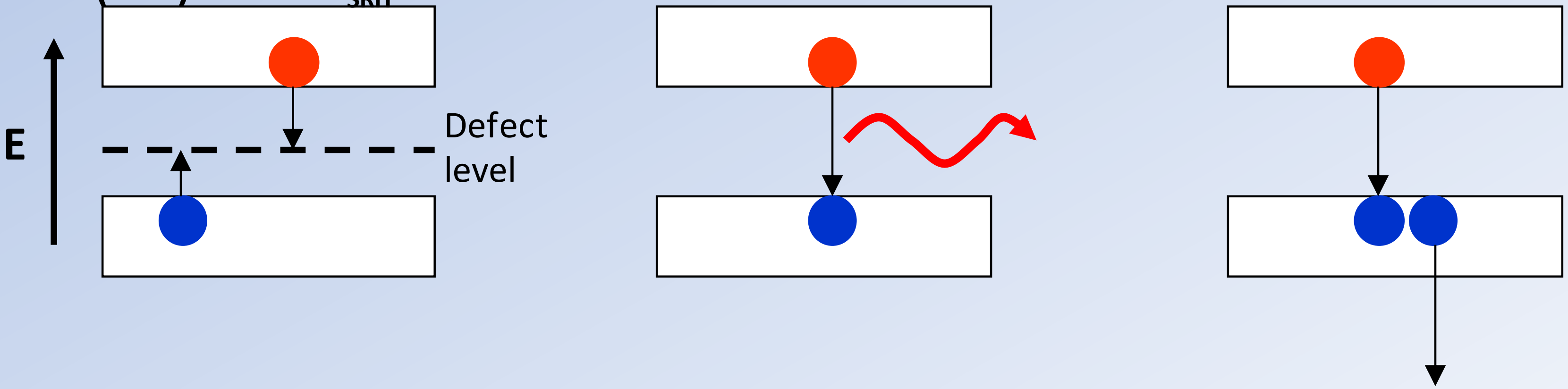
Growth

# However, bottleneck in quantum efficiency in narrow gap materials is typically Auger and not Shockley-Read-Hall scattering

Quantum Efficiency ≡ photons produced / electron-hole pair injected

$$= \frac{radiative\ rate}{radiative\ {+}SRH{+}Auger\ rate}$$

$$= \frac{B_{rad}n}{A_{SRH} + B_{rad}n + C_{Auger}n^2}$$

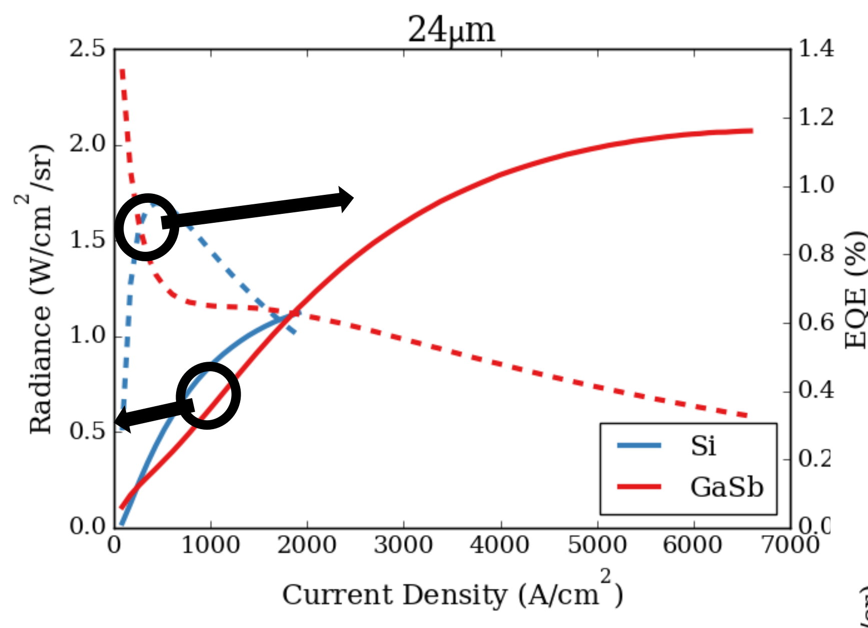


**Shockley Read Hall (SRH) rate = $A_{SRH}$**

**Radiative rate =$B_{rad}n$**

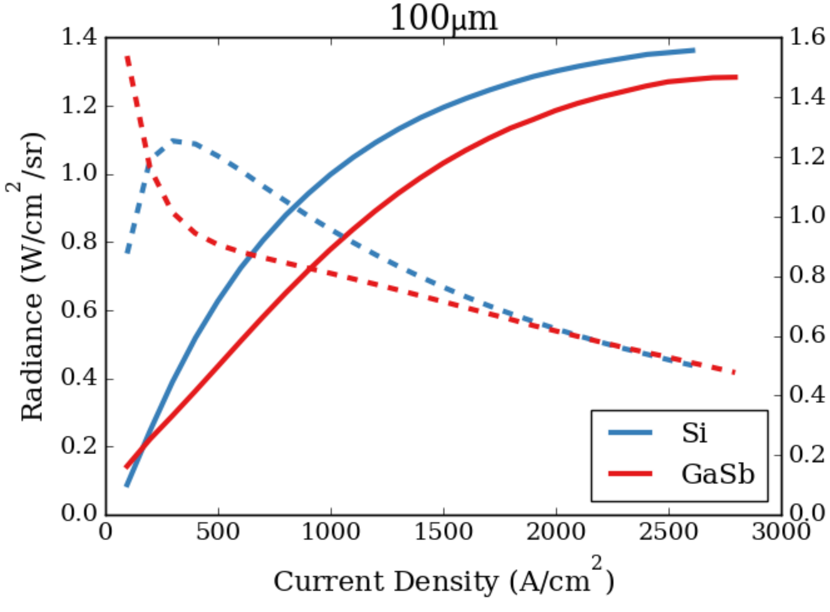
**Auger rate =$C_{Auger}n^2$**

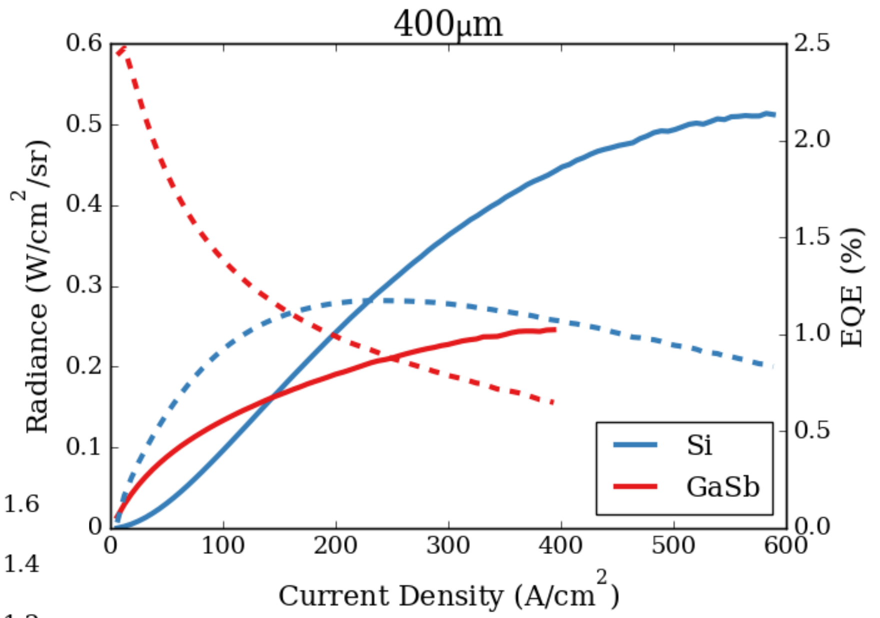
# Mid-infrared SLED on Si versus mid-ir SLED on GaSb – heating versus material quality



Si is way worse?

Si is a little better.





Si is way better!

A.J. Muhowski etal., J.P. Prineas*J. Cryst. Growth* **507**, 46 (2018)

# Mid-infrared SLED on Si versus mid-ir SLED on GaSb – recap

- Why grow Si substrates?
  - Less brittle and potentially cheaper
  - Better thermal and optical properties
- What holds growth on Si back?
  - Thick buffer layers required
  - Lower material quality
  - Defects cause failure at high current densities
- Preliminary result
  - At high injection, improvements from Si thermal conductivity and Auger bottleneck outweigh reduced material quality

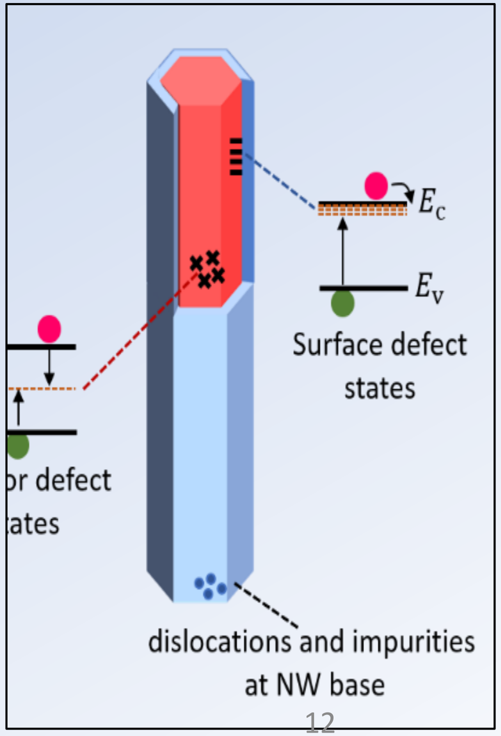
# Dislocation-free growth of InAs nanowires on (111) Si

❖ Why study nanowires on Si substrates?

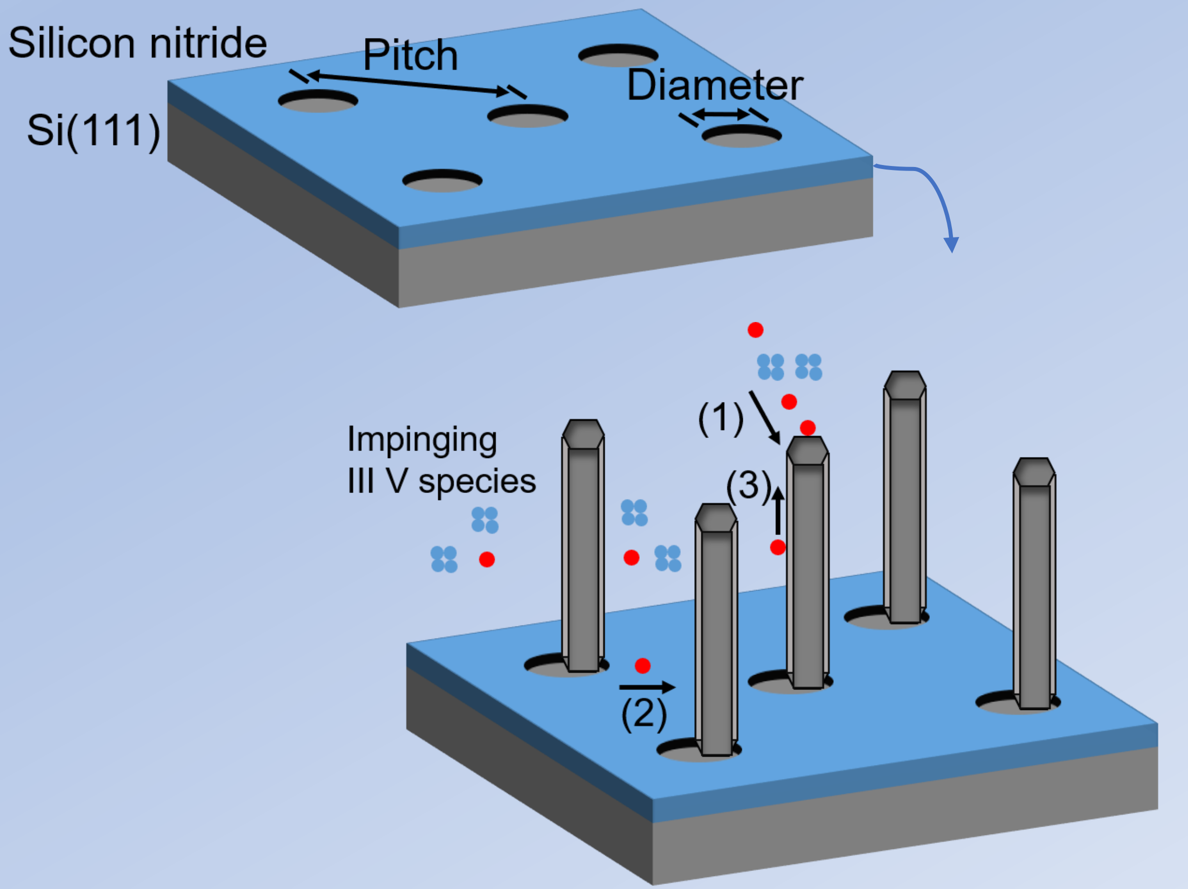
- Accommodation of strain without misfit dislocation
- Growth can be 5x-10x faster
- Easier to extract light due to lower effective index (e.g. ~ 1.25 vs 3.5)

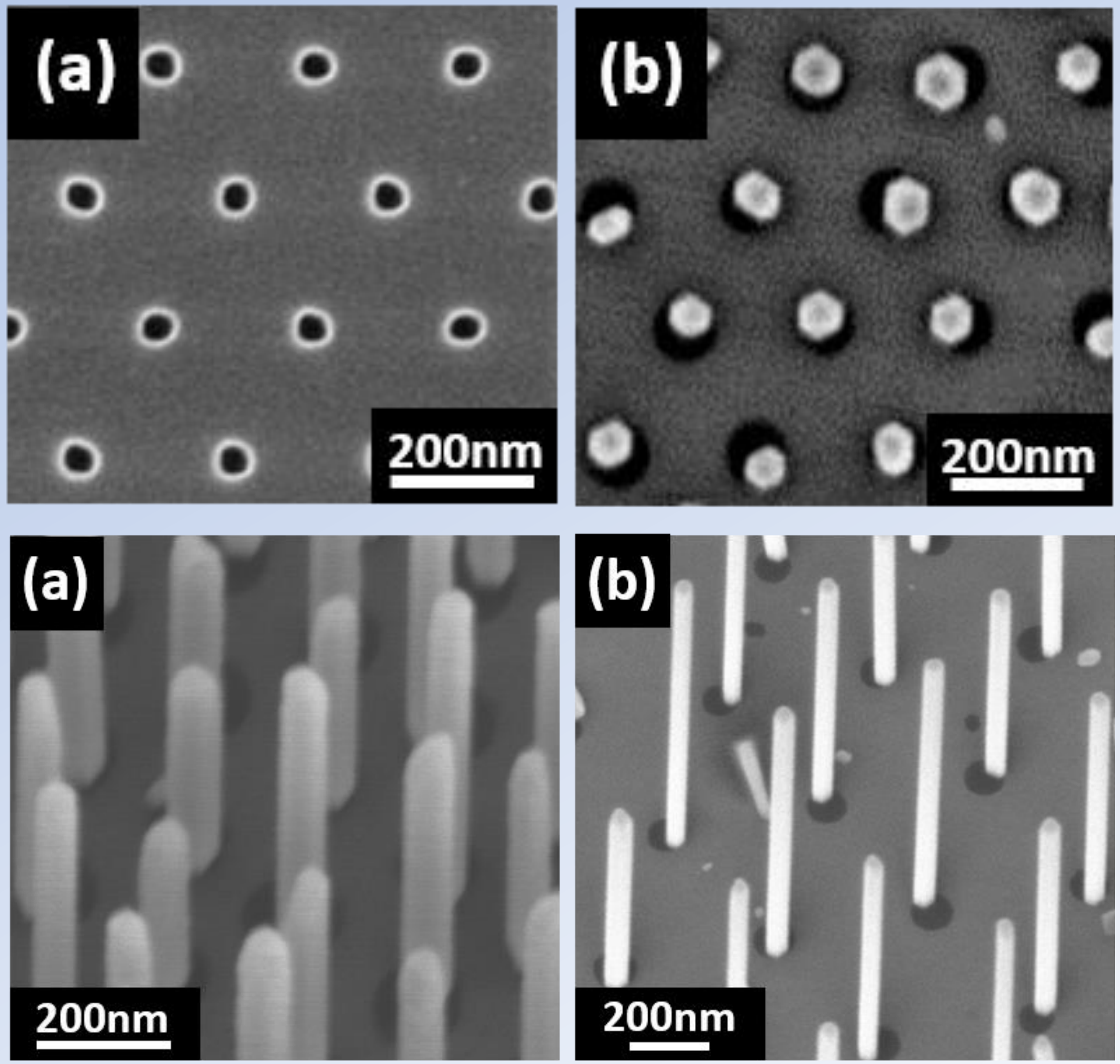
❖ Some challenges and questions

- Wurzite (instead of zincblende) crystal has unexplored bandstructure
- High surface-to-volume ratio believed to cause short carrier lifetime
- Interior carrier lifetime unknown (crystal defects such as polytypism, twinning, stacking faults observed)
- Is a “buffer layer” needed?



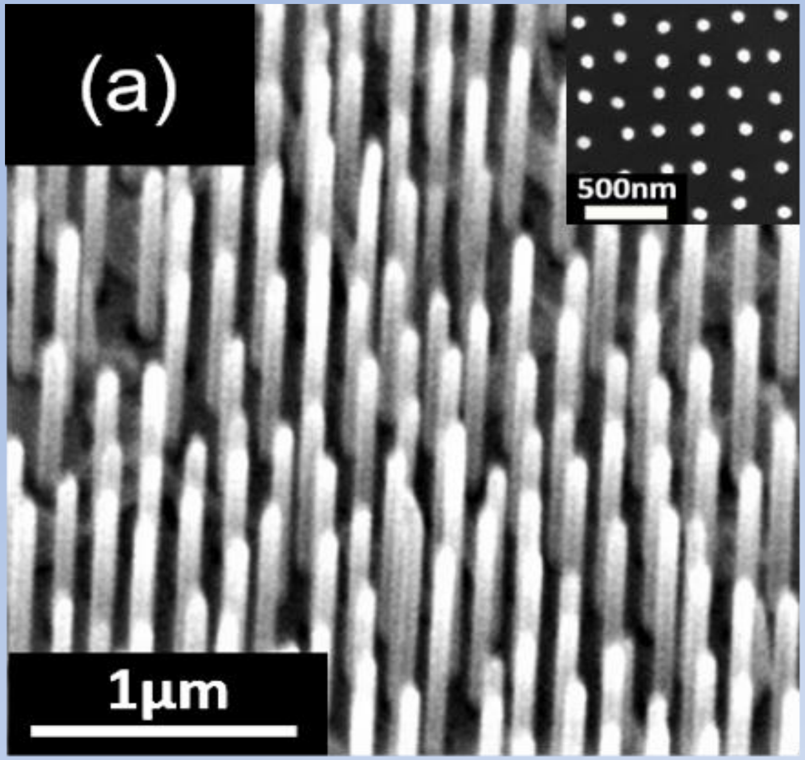
# The first study was on InAs nanowires on (111) Si grown by selective area epitaxy (MBE)



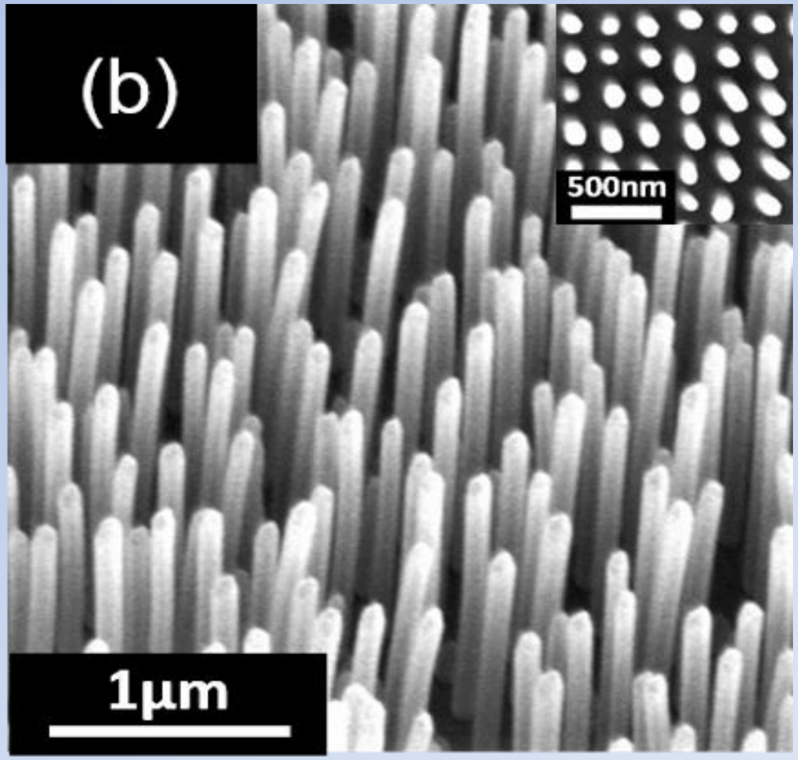


X. Li etal., J.P. Prineas *Nano Lett.* ***19****, 990-96 (2019)*

# Properties of both InAs nanowires, and InAs/InAlAs core shell nanowires were studied



InAs nanowires

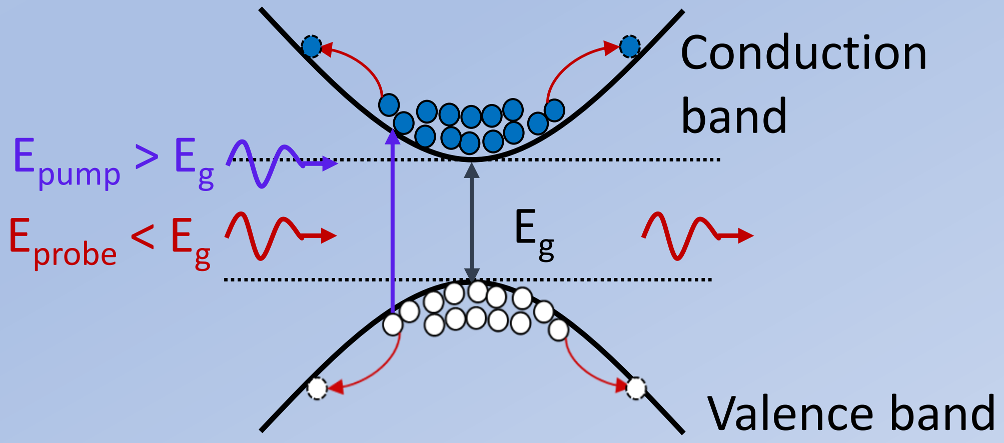


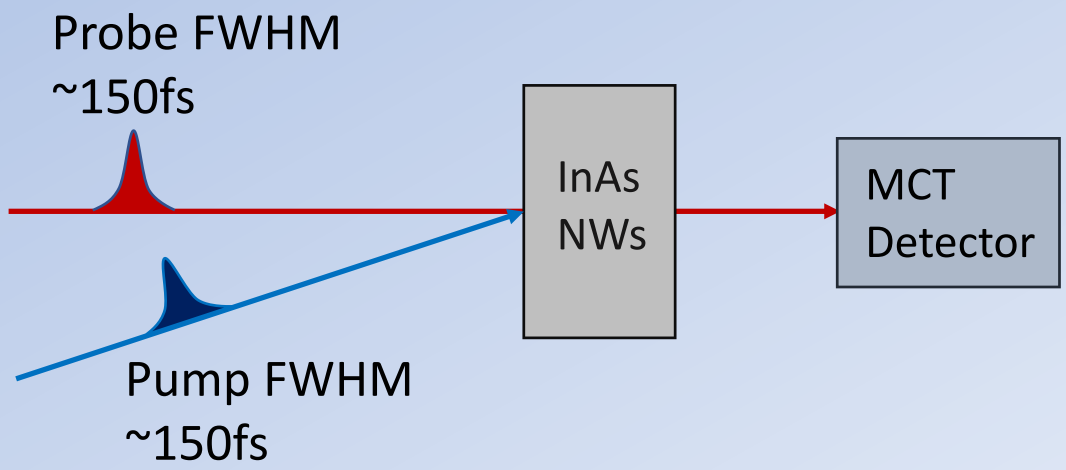
InAs/InAlAs core shell nanowires

Goal was to measure the material recombination coefficients

Acknowledgement of collaborator Prof. Gregor Koblmueller, Julian Treu, and Lukas Stampfer

# Carrier dynamics were characterized by pump-probe differential transmission

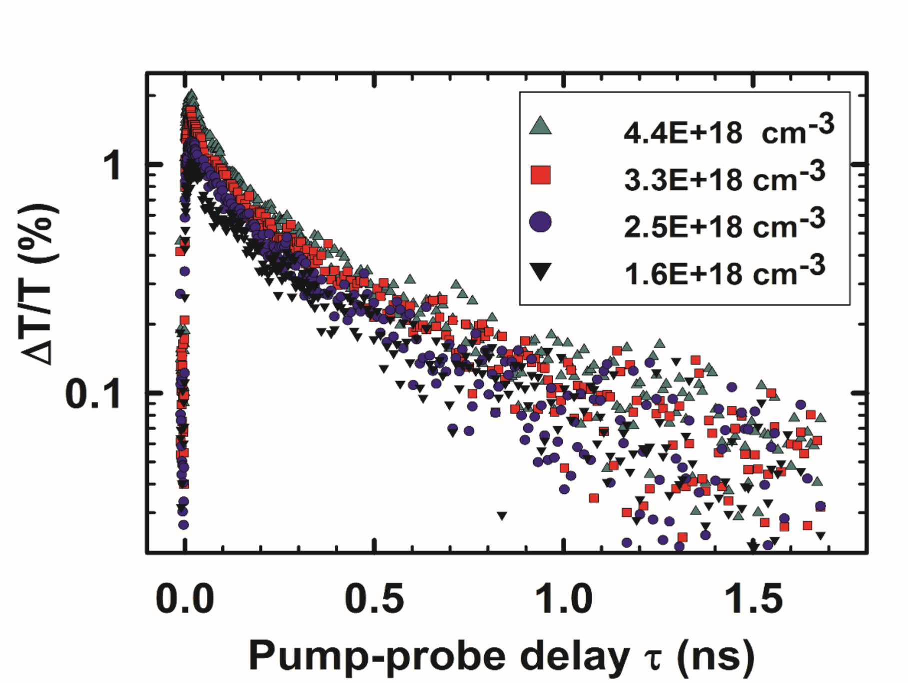


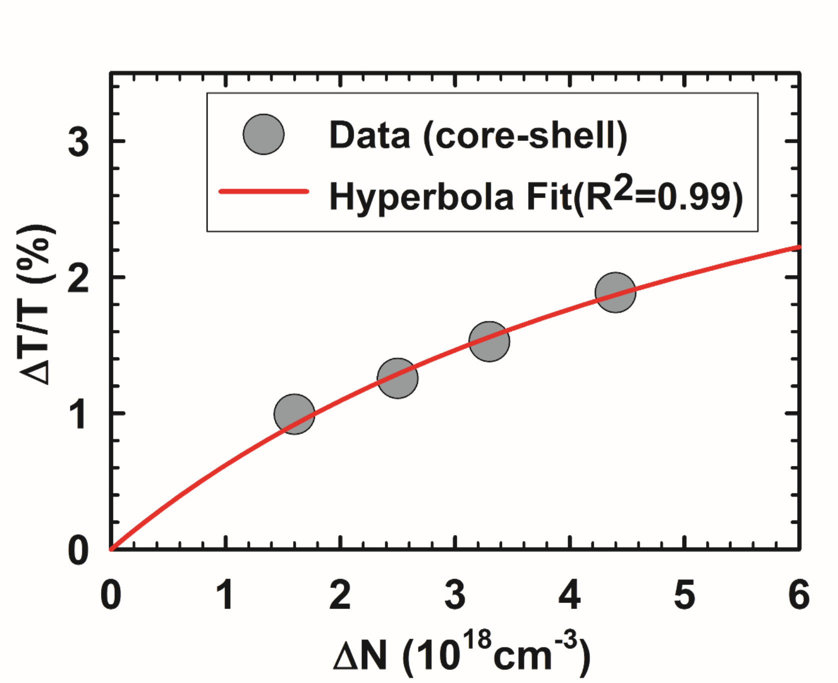


Above bandgap pump generates excess carrier density ΔN ⟷ Differential transmission ΔT/T of below gap probe which detects free carriers

Measure ΔT/T vs. pump-probe delay

# Use ΔT/T vs delay and response curve to obtain R(ΔN) versus carrier density

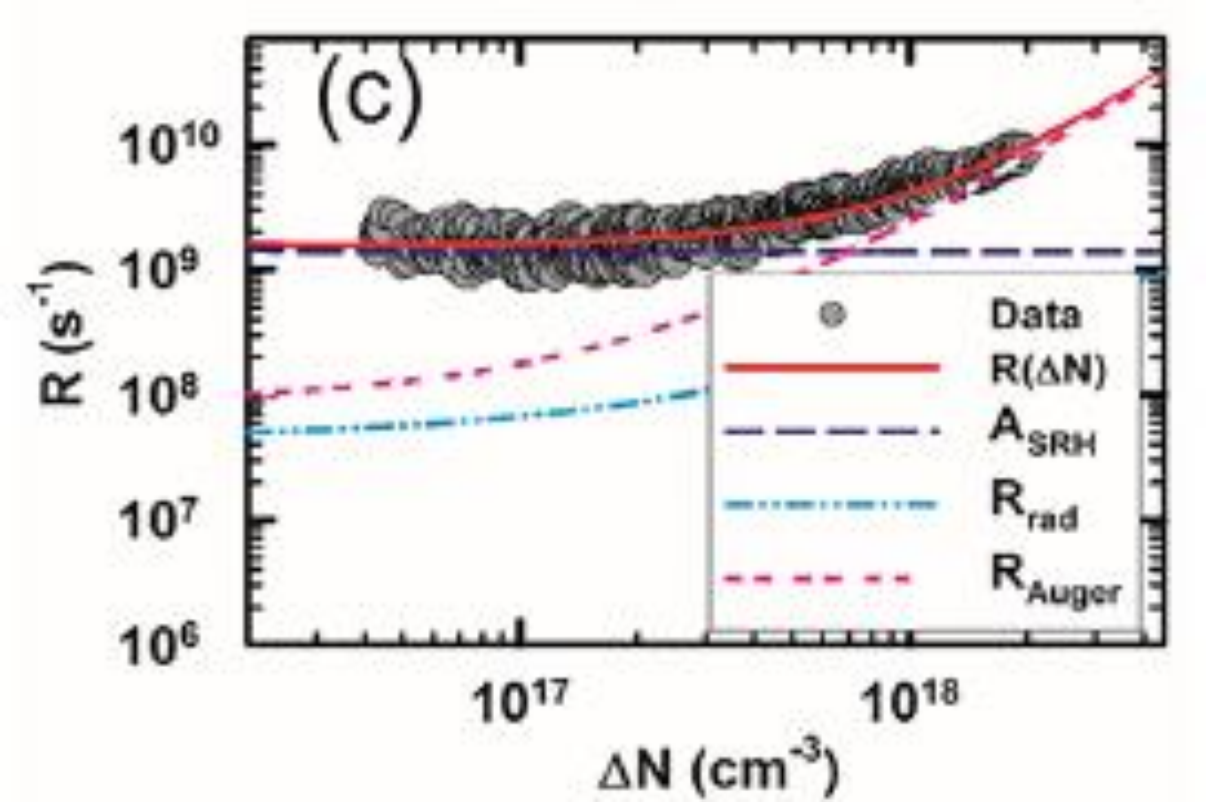




$$R(\Delta N) \equiv \frac{-1}{\Delta N}\frac{\partial \Delta N}{\partial t} = \frac{-1}{\Delta N} \times \frac{\partial(\Delta T/T)}{\partial t} \times \frac{\partial \Delta N}{\partial(\Delta T/T)}$$

# Use ABC analysis to obtain Shockley-Read-Hall and Auger coefficients

$R(\Delta N)$



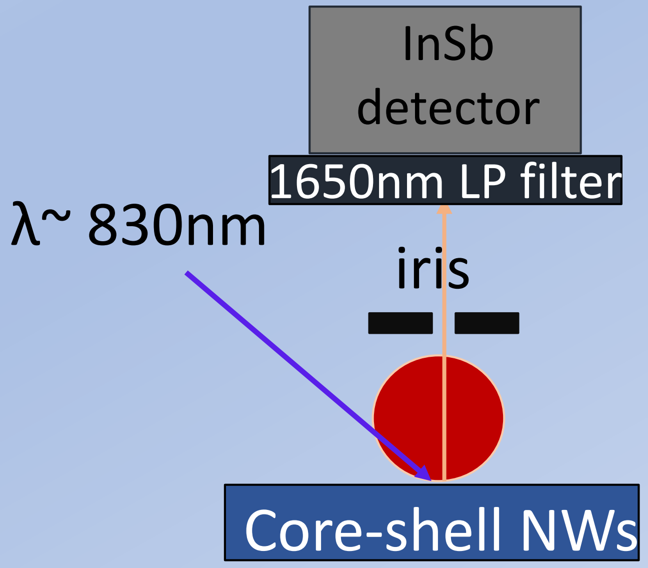
Fit experimental curve with:

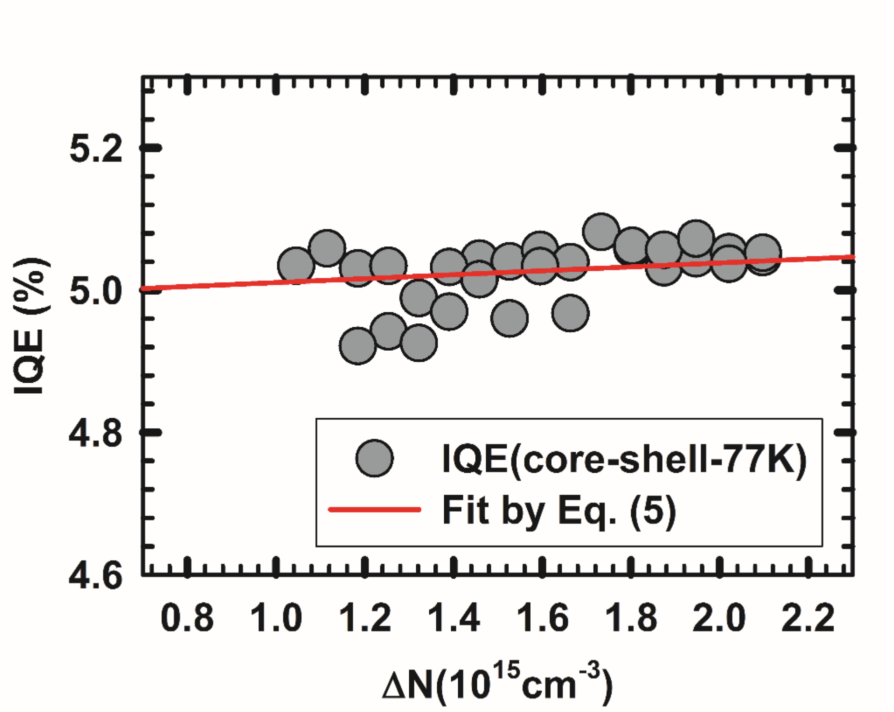
$$R(\Delta N) = A_{SRH} + B_{rad}\, n + C_{Auger} n^2$$

with $n = \Delta N + nb$

to obtain $A_{SRH}$ and $C_{Auger}$

# $B_{rad}$ obtained independently through quantum efficiency measurements

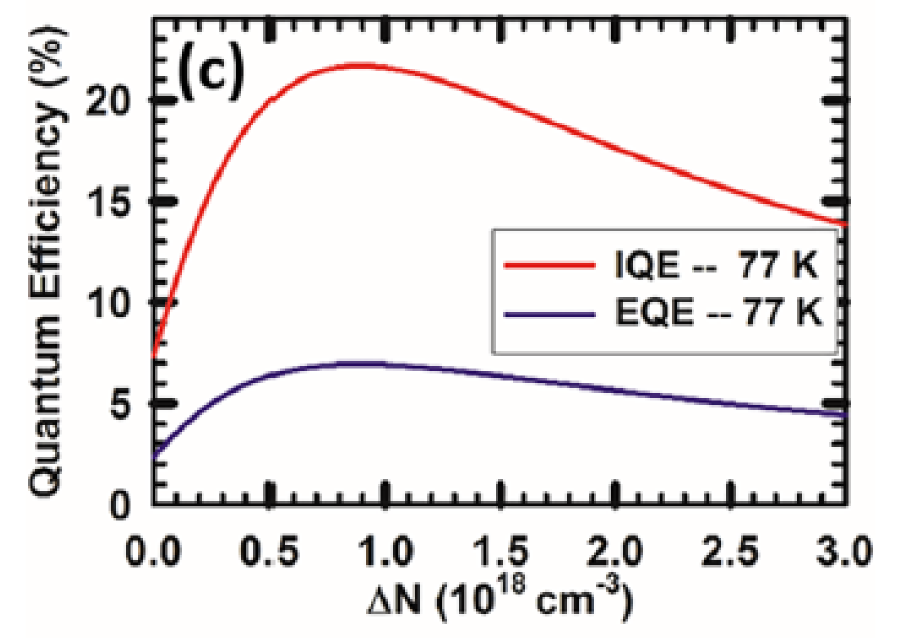




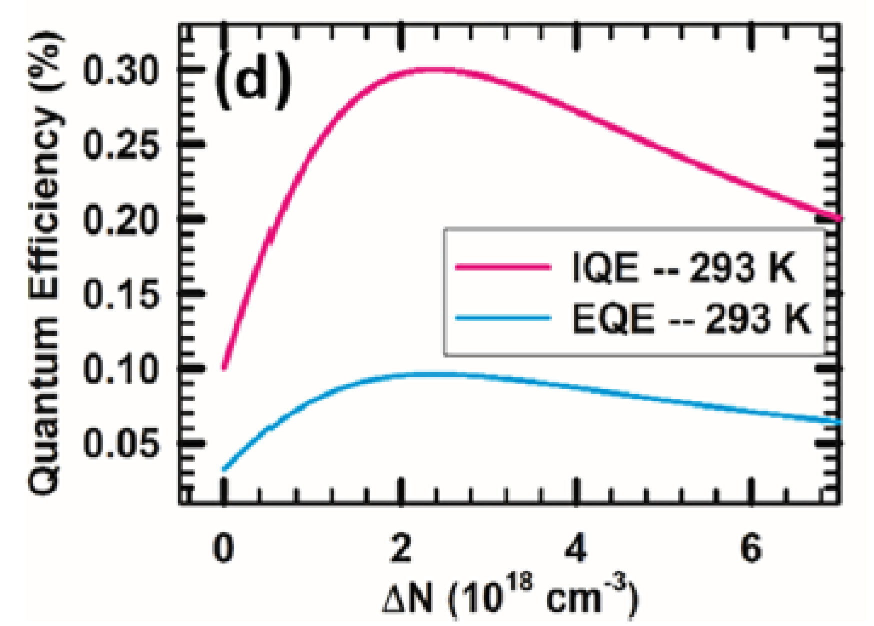
$$IQE = \frac{B_{rad}\Delta N}{R(\Delta N)}$$

Emission wavelength found to be 2.7 µm

# Auger coefficient was found to be ~10x smaller than zincblende planar materials; low temp EQE is very high

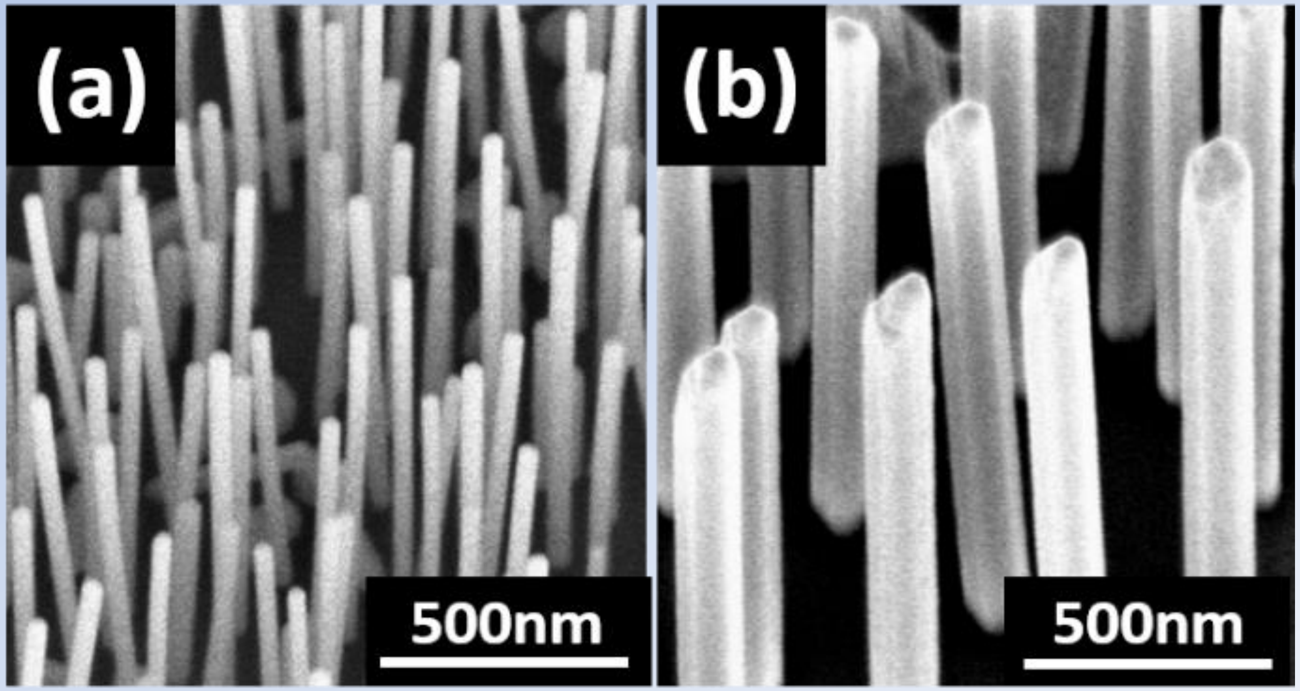


| Coefficient | 77K | Room temp |
|---|---|---|
| $A_{SRH}$ ($s^{-1}$) | $(1.38\pm0.15)\times 10^{9}$ | $(6.78 \pm 0.18) \times 10^{9}$ |
| $B_{rad}$ ($cm^3/s$) | $(6.80 \pm 0.04) \times 10^{-10}$ | $(1.42 \pm 0.16) \times 10^{-11}$ |
| $C_{auger}$ ($cm^6/s$) | $1.26 \pm 0.15 \times 10^{-27}$ | $8.23 \pm 0.44 \times 10^{-28}$ |



# The second study was on InAs/InAlAs nanowires on (111) Si grown by self nucleation (MBE)

- Pinholes in porous SiOx layer used instead of etched, patterned holes
- Si substrates were simply etched in 2% hydrofluoric (HF) acid and pretreated with 30% hydrogen peroxide ($H_2O_2$) for oxide regrowth



K. Zhang, X. Li, W. Dai, F. Toor, J.P. Prineas, *Nano Lett.*, http://dx.doi.org/10.1021/acs.nanolett.9b00517. (2019)

# Recombination rates at the surface, interior, and ends of the nanowire were resolved from geometric dependencies

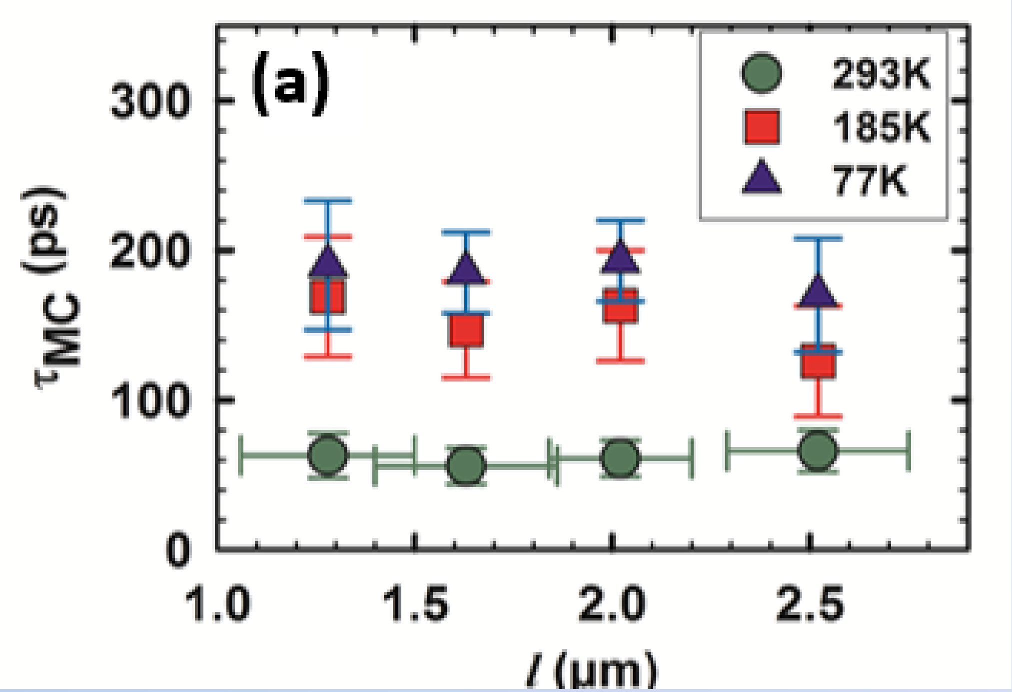
- Nanowire length varied by changing the growth time (1.2 to 2.5 µm)

- Nanowire diameter varied (40 nm to 129 nm) by:
  - changing the thickness of the regrown $SiO_2$ on Si (111),
  - changing both the true V/III ratio and growth time

- The surface recombination velocity S, and interior recombination rate $R_{interior}$ extracted by studying the geometrical dependence:

$$\frac{1}{\tau_{MC}} = \frac{4S}{d} + R_{interior}$$

# The nanowire minority carrier lifetime was independent of nanowire length



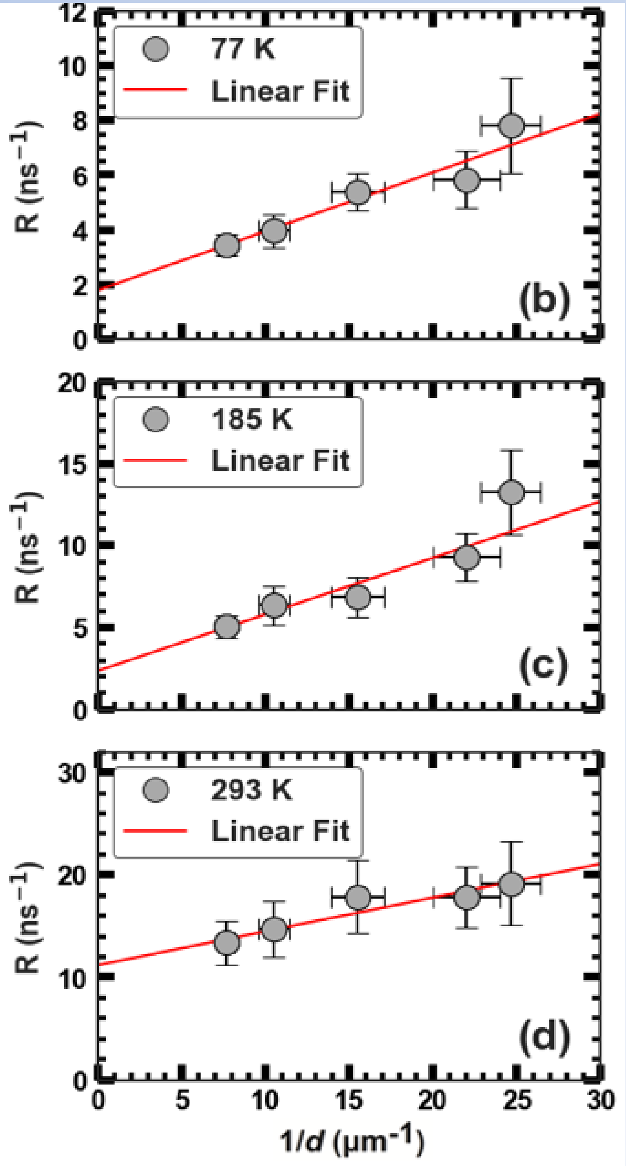
Result suggests no “buffer” segment or pedestal needed to protect against:

- substrate contamination
- substrate-NW interfacial misfits

# Surface and interior recombination rates were separated and compared

| | **77 K** | **185 K** | **293 K** |
|---|---|---|---|
| $S(\,cm \cdot s^{-1})$ | $5388 \pm 1596$ | $8615 \pm 2500$ | $8250 \pm 5145$ |
| $R_{interior}\ (ns^{-1})$ | $1.79 \pm 0.76$ | $2.35 \pm 1.27$ | $11.2 \pm 3.1$ |

- Surface recombination velocities comparable to planar InAs / air
- The surface and interior recombination rates equal for d = 70.1 nm, 17.1 nm at 77 K, 293 K, respectively



# InAs/InAlAs core shell nanowires – key findings

- Selective area grown, wurzite NWs show 10x lower Auger scattering rates than comparable planar zincblende materials, and high EQE at low temperatures, suggesting potential as a low cost, mid-infrared emitter
- Self-nucleated NWs show thick “buffer layers” not needed to avoid material degradation for growth on Si
- Self-nucleated NWs show interior recombination rate rather than surface recombination limits NW carrier lifetime for most diameters at room temperature, contrary to expectation